USAARL REPORT NO. 79-5

HOW TO MEASURE THE BURN-PREVENTIVE CAPABILITY OF NON-FLAMMABLE TEXTILES: A COMPARISON OF THE USAARL PORCINE BIOASSAY TECHNIQUE WITH MATHEMATICAL MODELS

By

Francis S. Knox, III
Thomas L. Wachtel
Stanley C. Knapp

March 1979

U.S. ARMY AEROMEDICAL RESEARCH LABORATORY
FORT RUCKER, ALABAMA 36362

USAARL

NOTICES

Qualified Requestors

Qualified requestors may obtain copies from the Defense Documentation Center (DDC), Cameron Station, Alexandria, Virginia. Orders will be expedited if placed through the librarian or other person designated to request documents from DDC.

Change of Address

Organizations receiving reports from the U.S. Army Aeromedical Research Laboratory on automatic mailing lists should confirm correct address when corresponding about laboratory reports.

Disposition

Destroy this report when it is no longer needed. Do not return it to the originator.

Disclaimer

The views, opinions, and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other official documentation.

In conducting the research described in this report, the investigator(s) adhered to the "Guide for Laboratory Animal Facilities and Care," as promulgated by the Committee on the Guide for Laboratory Animal Resources, National Academy of Sciences-National Research Council.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE *(When Data Entered)*

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE *(and Subtitle)* HOW TO MEASURE THE BURN-PREVENTIVE CAPABILITY OF NON-FLAMMABLE TEXTILES: A COMPARISON OF THE USAARL PORCINE BIOASSAY TECHNIQUE WITH MATHEMATICAL MODELS		5. TYPE OF REPORT & PERIOD COVERED
		6. PERFORMING ORG. REPORT NUMBER USAARL Report No. 79-5
7. AUTHOR(s) F. S. Knox, III, T. L. Wachtel, and S. C. Knapp		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS US Army Aeromedical Research Laboratory P. O. Box 577 Fort Rucker, AL 36362		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 6.27.73.A, 3E762173A819, 015
11. CONTROLLING OFFICE NAME AND ADDRESS US Army Medical Research & Development Command Fort Detrick Frederick, MD 21701		12. REPORT DATE March 1979
		13. NUMBER OF PAGES 16
14. MONITORING AGENCY NAME & ADDRESS*(If different from Controlling Office)*		15. SECURITY CLASS. *(of this report)* Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT *(of this Report)*

This document has been approved for public release and sale; its distribution is unlimited.

17. DISTRIBUTION STATEMENT *(of the abstract entered in Block 20, if different from Report)*

18. SUPPLEMENTARY NOTES

This is a reprint of an article published in Burns: The Journal of the International Society for Burn Injuries, 5(1): 19-29, 1978.

19. KEY WORDS *(Continue on reverse side if necessary and identify by block number)*

Swine
Skin
Burns
Simulated Postcrash Fires
Mathematical Models
Computer Simulation
Thermal(ly) Protective Clothing
Flight Suits
Heat Transfer

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

See back of form.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE *(When Data Entered)*

20. ABSTRACT

Nonflammable fabrics are used extensively as an insulating thermal barrier to protect the wearer from injury from an extrensic thermal source. The US Army Aeromedical Research Laboratory (USAARL) porcine cutaneous bioassay technique has been used to determine the burn prevention capabilities of nonflammable fabrics. The results of this technique correlate well with clinical observations, but are logistically difficult and expensive to conduct. The ideal method for testing fabric samples would be to use a physical thermal sensor to measure the heat flux transmitted through or emanating from a fabric and convert this measured heat flux to a predicted burn depth. This paper presents the data from over 1500 burn sites on 95 domestic white pigs in which the bioassay method was used in conjunction with calorimeters exposed to the same fire. Two mathematical models, one analytic and the other empirical, are described. The results of these models are compared with the results of the bioassay technique in the evaluation of four nonflammable fabrics. The comparison shows that the models are efficient tools for routine evaluation of nonflammable fabrics. The models provide a basis from which to develop better test methods for children's sleepwear, nursing home textiles, and other thermally protective fabrics.

Burns, 5, 19 29 *Printed in Great Britain*

How to measure the burn-preventive capability of non-flammable textiles: a comparison of the USAARL porcine bioassay technique with mathematical models

Francis S. Knox III

Department of Physiology and Biophysics, Louisiana State University Medical Center, Shreveport

Thomas L. Wachtel

Regional Burn Treatment Center, University of California, San Diego

Stanley C. Knapp

Commanding Officer, United States Army Aeromedical Research Laboratories, Fort Rucker, Alabama

INTRODUCTION

THE severity of thermally induced cutaneous injury can be related to the existence of thermal sources and fuels such as space heaters and inflammable fabrics and the duration for which energy transfer to skin takes place. Prevention of such injury can be obtained by the elimination or control of thermal sources and/or the introduction of non-flammable fabrics. Non-flammable fabrics, by virtue of their thermal stability, will not usually act as a secondary thermal source, and can serve as an insulating thermal barrier which protects the wearer from injury from an extrinsic thermal source.

The US Army Aeromedical Research Laboratory (USAARL) porcine cutaneous bioassay technique has been used to determine the burn prevention capabilities of non-flammable fabrics destined for use in thermally protective flight suits (Knox et al., 1974; Knox et al., 1978a, b; Knox et al., 1979). In this method domestic white pigs (an animal model for human skin) are exposed to a simulated post-crash fire while protected by test fabrics. The sub-fabric burn injury is rated by clinical observation (Wachtel et al., 1978) and by depth measurements made on sections of burn wound biopsies (Knox et al., 1978c). These data provide outcomes that are understood by physician, physiologist and engineer alike but the bioassay method is costly and tedious.

The ideal method for testing fabric samples would be to use a physical thermal sensor such as a calorimeter or skin simulant to measure the heat flux transmitted through or emanating from a fabric and to convert this measured heat flux to a predicted burn depth. To do this with any degree of accuracy requires a good mathematical model. This idea has been explored previously, but these mathematical models which generate burn predictions (Stoll and Greene, 1959; Aerotherm Corporation, 1970; Takata, 1974;

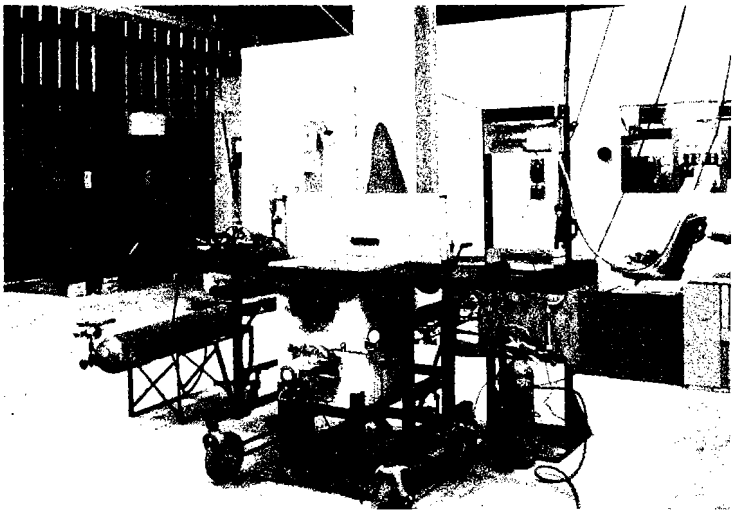

Fig. 1. The US Army Aeromedical Research Laboratory post-crash fire simulation furnace with a water cooled shutter mounted in a movable animal holding table. A template is shown in place. (Copyright reserved.)

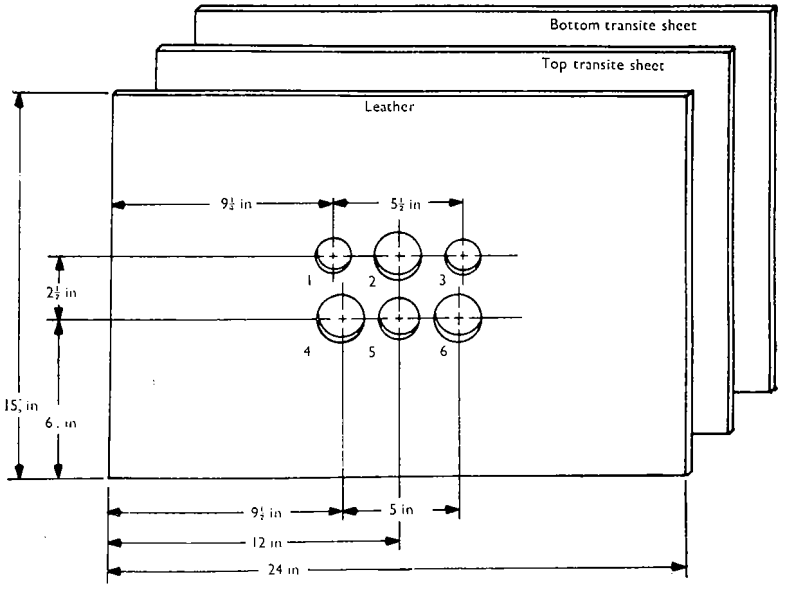

Fig. 2. Six-holed template used to define burn sites on pigs and to hold sensors. Hole no. 5 held a slug calorimeter for all tests. Holes 1, 3, 4 and 6 were used for sensors or burn sites and hole 2 was used to hold a HyCal calorimeter or to define a burn site. (Copyright reserved.)

Knox et al., 1978b) from measured thermal transfer are not sufficiently accurate.

This paper presents data from over 1500 burn sites on 95 domestic white pigs in which the bioassay method was used in conjunction with calorimeters exposed to the same fire. From these studies two mathematical models were developed, one analytic and the other empirical (Knox et al., 1978b). These models are compared with the results and logistics of the bioassay technique in

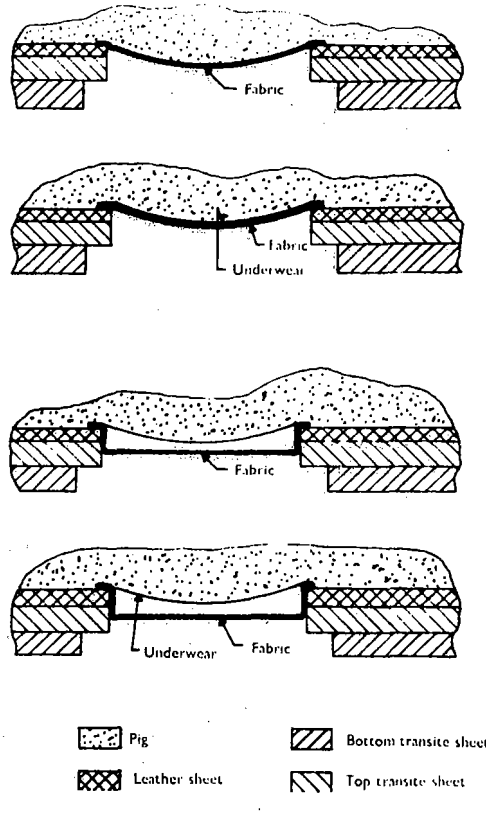

Fig. 3. Cross-section of pig and template showing placement of fabrics. Only the top configuration with the fabric touching the skin is discussed in this paper. (Copyright reserved.)

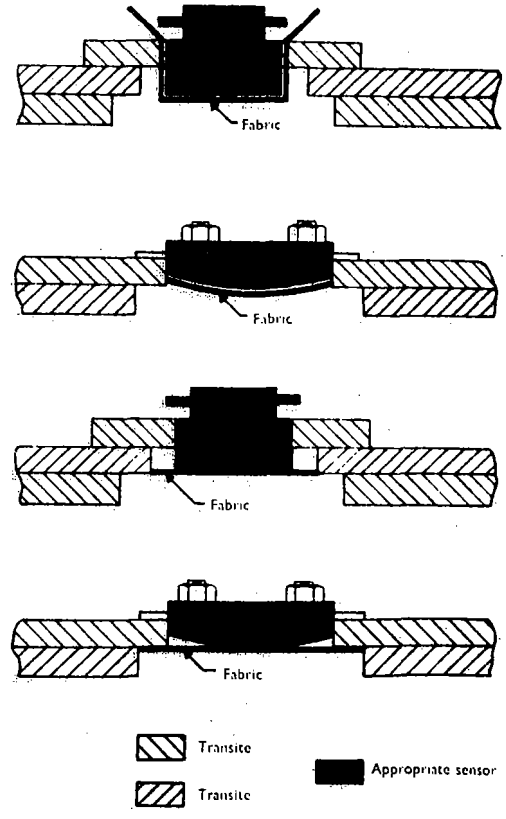

Fig. 4. Cross-section of template holding Aerotherm sensors (top and third down) and Fabric Research Lab. sensors (second and bottom). Fabrics in this study were touching the sensors. (Copyright reserved.)

the evaluation of four non-flammable fabrics. This comparison shows that the models are efficient tools for routine evaluation of non-flammable fabrics but will require further development to improve their accuracy. The models provide a basis from which to develop better test methods for children's sleepwear, nursing home textiles and other thermally protective fabrics.

METHODS AND MATERIALS

In all, 95 white domestic pigs weighing 10–13 kg were procured, quarantined, freed of internal and external parasites and verified to be healthy before use in this study. In conducting this research the investigators adhered to the *Guide for Laboratory Animals, Facilities and Care* (National Academy of Sciences, National Research Council). The animals were housed in a covered outdoor vivarium and weighed 43·9 ± 6·6 kg at the time of the experiments.

The pigs were fasted overnight, premedicated with atropine (0·04 mg/kg) and fentanyl-droperidol (0·1 ml/kg), intubated and anaesthetized with halothane USP. All the hair was closely clipped with a no. 40 clipper head (Wachtel et al., 1977). The anaesthetized pigs were placed on a rolling animal carriage with an electrically activated, pneumatically operated, water cooled, shutter system (Knox et al., 1974; Knox et al., 1978a; Knox et al., 1979). Each animal received up to four separate exposures (20 burn sites) of from 0·58 to 14·29 s duration to a standardized thermal source. The thermal source was a JP-4 fuelled furnace which could deliver 0·7 to 3·92 cal $cm^{-2} s^{-1}$ (70–90 per cent of the energy was radiative) (*Fig.* 1) (Knox et al., 1974).

Table I. 24-hour evaluation

Computer No.	*Laboratory grade*	*Surface appearance*	*Hair removal*	*Additional information*	*Burn depth on cut section*	*Anatomical depth*
0	0	Normal skin	Difficult	Pliable Normal skin	Zero	No burns
1	1–	Mild erythema (pink)	Difficult	Painful		Epidermal
2	1	Moderate erythema (red)	Difficult	Pliable		Epidermal
3	1+	Severe erythema (dark red or purple)	Difficult		All epidermis/ dermis discoloured	Epidermal
4	2–	Whitish crests 10–30% with red or purple valleys 70–90%	Difficult	Painful		Superficial
5	2	White crests 50% with red valleys 50%	Difficult	Pliable	30% dermis reddish brown	Intradermal
6	2+	Mostly white 80% with few red valleys 20%	Difficult		40% dermis	
7	3–	White	Difficult	Cuts harder Pliable	50% dermis	Deep intradermal
8	3	White	Some difficulty		60% dermis	
9	3+	Tannish	Easy		All dermis coagulated and fat slightly discoloured	
10	4–	Majority of epithelium intact with < 5 mm vesicles removed	Easy	Spotted and leathery but cuts hard	All dermis + 2 mm fatty discoloured and haemorrhage	Subdermal
11	4	Areas of coagulate red and white (pepperoni)	Very easy			Subdermal
12	4+	Purple and white (coagulated)	Very easy		Coagulated and contracted	Subdermal
13	5–	Clear gelatine surface with purple and white geographic below	Very easy		Haemorrhage into fat and discoloured 5 mm deep	Subdermal
14	5	Hazy gelatin with homogeneous dark (faded), purple and white	Burned off or buried in coagulation			Subdermal
15	5+	Dark brown to black coagulated surface	Burned off or buried in coagulation			Subdermal

The pigs were protected by a template containing five circular exposure sites and a slug calorimeter (*Fig.* 2). For some experiments four of these sites were covered with one of four fabrics with one left as a non-fabric control site (*Fig.* 3). In one such experiment 20 pigs were protected by 4 fabrics with each fabric receiving 20 replications in each of 4 modes of application and appearing in each separate exposure site according to a Latin square (Knox et al., 1979).

Just before and just after the exposure of each of these 20 pigs to a well-controlled fire (5-s exposure to $3{\cdot}07 \pm 0{\cdot}16$ cal cm^{-2} s^{-1}) a 'test template' was exposed to the same fire. This

Table II. Clinical grading system: immediate evaluation

Computer no.	*Laboratory grade*	*Descriptive term*	*Surface appearance*	*Hair removal*	*Additional information*	*Burn depth on cut section*
0	0	Normal skin	Normal skin	Difficult	Normal skin Pliable Pain to needle stick	Zero
1	1–	Red burn	Mild erythema (pink)	Difficult	Pliable	Upper epidermis
2	1		Moderate erythema (red)	Difficult	Painful	50% of epidermis
3	1+		Severe erythema (dark red or purple)	Difficult	Hot to touch	All epidermis
4	2	Spotted white burn	Patchy coagulation 10–30% white and 70–90% red or purple	Difficult	Pliable	0–5% dermis
5	2		50% white (crests) and 50% red or purple (valleys)	Difficult	Painful	5–10% dermis
6	2+		70–80% white (crests) and 20–30% red or purple (valleys)	Difficult	Hot to touch	10–15% dermis
7	3–	White burn	Uniform coagulation >90% white <10% red	Some difficulty	Pliable	25% dermis
8	3		Shiny or opalescent white	Fairly easy	Some pain	75–80% dermis
9	3+		Dull white or tan: dry-looking surface	Easy	No blebs	All dermis, but epidermis attached on cutting
10	4–	Steam blebs	Multiple vesicles that look like crumpled tissue paper	Very easy	Pliable	All dermis + 1 mm fat discoloration epithelium carries away
11	4		Raised delicate bleb	Very easy	No pain	All dermis + 1–2 mm fat
12	4+		Broken large delicate blebs	Very easy		Dermis opalescent white coagulation 3–4 mm fat
13	5–	Carbonation	Very charred blebs around periphery	Very easy but often burned off	Decreased pliability no pain	All dermis 4–5 mm fat discoloured
14	5		50% charred, usually no blebs around periphery	Very easy but often burned off	No pain, non-pliable	All dermis
15	5+		>70% charred, no blebs	Very easy but often burned off	Hard and non-pliable No pain	All dermis >6 mm fat

Table III. Histopathological and burn depth grading definitions

Grade	*Description*	*Approximate depth (μm)*
0	No thermal damage	0
1	Cell damage without acidophilisim	1–20
2	Partial epidermal acidophilisim	25–50
3	Complete epidermal acidophilisim	50–100
4	Partial dermal–epidermal separation	100–150
5	Complete dermal–epidermal separation	150–250
6	Superficial dermal	300–500
7	Mid-dermal	600–1000
8	Deep dermal	1100–1500
9	Complete dermal to adipose border	1600–2000
10	Adipose	>2000

template held 6 heat sensors, 2 made by Aerotherm for their 'Thermoman'*, 2 skin simulants made by the Fabric Research Laboratories, a slug calorimeter and a HyCal asymtotic calorimeter. The first 4 sensors were protected by the same 4 fabrics used on the intervening pigs while the slug and HyCal calorimeters monitored the fire directly (*Fig.* 4).

The severity of the resultant burn lesions was evaluated immediately and at 24 h post burn and documented with colour photographs. A clinical grade (*Tables I, II*) was assigned and recorded immediately after exposure and again 24 h later (Wachtel et al., 1978). This scheme of grading employed the surface appearance, sensation, tactile response, hair tenacity and appearance on cut section.

A biopsy was taken from each site 24 h after exposure. This specimen included the area representing the highest clinical grade as well as contiguous adjacent normal tissue for comparison. Sections stained with haematoxylin and eosin were graded according to the criteria in *Table III* (Lyon et al., 1955; Knox et al., 1978). In addition to this grade, actual burn depth was measured optically, together with measurements of the normal epidermal and dermal thickness.

A computerized data base was developed to manage the data from all experiments. For each burn site the following items were recorded: pig number, site number, smoke density, template type, exposure time, heat flux, furnace wall temperature, initial pigskin temperature, fabric type, skin condition (natural or blackened), clinical grade, histopathological grade, epidermal thickness, dermal thickness, burn depth (epidermal–dermal border to burn), length of hair, date, time, ambient temperature per second, independent reading for histopathological grade and burn depth versus thickness of normal dermis and epidermis, corrected burn depth, computer-calculated flux, computer-calculated exposure time and data quality number. In all, there are 45 752 entries for 1634 exposures from 75 pigs in the data base. The data can be retrieved via an interactive access program. Also available are other data files for furnace wall temperatures, heat fluxes, sensor responses and intraskin thermocouple responses all of which were recorded on FM magnetic tape and later digitized to 12-bit accuracy at 100 samples per second and stored on digital magnetic tape. Offline hard copy records include ambient temperature and humidity, regional hourly weather reports, pig weight, sex and data on skin cooling and water content.

The models and data base access programs were written in FORTRAN and run on a DEC PDP 11/40 minicomputer. Preliminary development of the analytical model was carried out on IBM 360 and 370 computers.

A multidiscriminate statistical model was derived from the experimental data and used to determine the importance of many variables. An analytical model was developed which assumes that the tissue damage after a burn injury procedes as a first-order chemical reaction dependent on tissue temperature and that total damage is merely the time integral of tissue damage during heating and cooling. It also takes into consideration boiling of tissue water, thermal shrinkage and tissue oedema which alter the measured depth of burn (Knox et al., 1978a, b).

* 'Thermoman' is an instrumented manikin developed under US Air Force Contract by Aerotherm Division of Accurex Corp.

Table IV. Comparison of burns observed in bioassay test with predictions of math models 1 and 2

Exposure time (s)•	*Flux (cal cm^{-2} s^{-1})*	*Skin temp. (°C)*	*Observed burn depth (10–4 cm)*•	*Predicted depth* Model 1	Model 2	*Calculated surface temp. (°C)* max. 1	max. 2	*Recorded temp (°C)† max.*
0·98±0·01	3·31	30	257±4	284	297	99·4	99·2	49·9
0·73±0·01	3·54	31·7	222±8	253	<222	76·7	94·0	69·6
3·0	3·54	29·4	1495¶	§	716	163·5	134·9	98·2
1·47±0·01	3·92	30·6	1020±303	513	570	96·1	103·0	97·9
3·07±0·01	2·60	28·1	611±239	654	719	126·5	103·0	—
0·99±0·01	2·68	26·1	72±3	281	<222	83·5	82·5	—
8·20±0·01	2·43	27·8	1488**	‡	2005	173·65	146·6	—
1·51±0·01	2·38	26·9	73±14	264	<222	77·9	89·8	—

* Mean±s.e.mean.
† Approximate depth of recording=100–200 μm.
‡ Ω Node 10>>>1 so no depth calculation possible.
§ Ω Node 10>1 interpolation scheme using nine nodes=1155·4.
¶ Only one observed depth available.
** Only one of five biopsies readable.
Model 1, no water boiling, low heat flow into fat, integration of $d\Omega/dt$ at 1-s intervals.
Model 2, water boiling (103°C), heat flow to fat increased, integration of $d\Omega/dt$ at 0·01-s intervals.

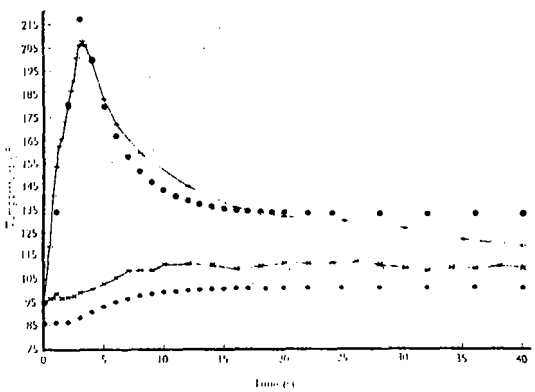

Fig. 5. Tissue temperature as a function of time at two different depths. Observed temperatures are shown as symbols connected by straight lines for depths of approximately 200 μm (above) and 2000 μm fat–dermal border (below). The output of a computer model (solid circles) which did not take into account water boiling or tissue cooling by blood. The 9 °F offset between the lower two curves is due to assuming that the starting surface temperature and the initial temperature at a depth of 2000 μm are identical. (Copyright reserved.)

RESULTS

The following data have been selected from the large data base in order to illustrate the comparison of the bioassay method with our current mathematical model. *Table IV* summarizes the observed burn depths after 8 exposures on 2 pigs. For comparison, the burn depths predicted by a model which does not take into account tissue water boiling (model 1) and by a model which does (model 2) are presented along with calculated surface temperatures. In the case of the first pig sub-surface (100–200 μm deep) temperatures were recorded with fine copper-constantan thermocouples. *Fig.* 5 shows a plot of tissue temperature at two different depths (100–200 μm and at the fat–dermal border) along with the calculated temperatures (model 1).

Table V summarizes the clinical grades, micrograde and burn depths associated with each of the four fabrics evaluated and reported elsewhere (Knox et al., 1979). Only the data for group 1 (single layer in contact with the skin) are reiterated here because the sensors were also covered by a single layer in contact with the sensor surface. *Table VI* summarizes the results from two sensors in which the recorded time–temperature profile was used to back calculate the incident time–heat flux profile which was in turn input to the mathematical model (model 2) to obtain a threshold depth (TD calc.). For comparison, the observed burn depth from the associated pigs protected by the same fabrics are also presented. Unlike the data in *Table V* which are mean values calculated across all 20 exposures on 5 different pigs, the observed depths (TD obs.) in *Table VI* are means within one pig. In either case the variance is large, which is typical of these kinds of experiments (Berkley, 1954; Knox et al., 1978a; Knox et al., 1979).

Table V. Summary of burn grades/depths by fabric (16)

Treatment	*Fabric*	*Clinical grade**			*Micro grade**			*Depth** (*μm*)		
Group I:	AFN	11·65	1·42	20	7·18	1·01	17	1313	608	15
Fabric in	PBI	11·74	1·82	19	6·59	0·94	17	908	542	15
contact	HT4	11·10	1·97	20	7·00	1·24	18	1033	537	13
with skin	NWN	12·30	1·78	20	7·11	0·96	18	1098	519	16
	Control	13·75	1·16	20	7·13	0·83	15	1149	539	14

* Mean ± 1 s.d. number of observations.

Table VI. Comparison of observed burn depth with burn depths calculated based on recorded thermal transfer

Test no.	T_o	*Exposure time (s)*	*Fabric**	*Absorptivity*	*TD obs.**	*TD calc.*
Sensor 2						
1	31·81	2·97	NWN	0·6	67	<222
2	32·22	2·97	AFN	0·6	274	222–444
3	32·22	4·97	HT4	0·6	926	761
6	28·61	4·97	NWN	0·6	728±457	752
7	27·22	4·97	HT4	0·6	705±553	450
8	31·11	4·97	PBI	0·6	1001±23	547
9	30·56	4·97	HT4	0·6	348±247	789
10	30·56	4·97	NWN	0·6	690±318	792
11	29·72	4·97	HT4	0·6	923±643	564
12	31·11	4·97	AFN	0·6	1588±127	598
Sensor 3						
1	31·8	2·97	PBI	0·9	201	565
2	32·2	2·97	HT4	0·9	48±16	563
3	32·2	4·97	PBI	0·9	512±53	929
6	28·61	4·97	AFN	0·6	512±270	728
7	27·2	4·97	NWN	0·6	728±456	677
8	31·1	4·97	NWN	0·6	1345±321	779
9	30·56	4·97	PBI	0·6	1002±23	794
10	30·56	4·97	HT4	0·6	923±643	567
11	29·72	4·97	AFN	0·6	1133±543	1593
12	31·1	4·97	NWN	0·6	857±214	782

* AFN, Standard USAF Nomex®; PBI, Polybenzimidazole; HT4, experimental high temperature polymer; NWN, New Weave Nomex®.

DISCUSSION

Extensive biomedical investigation of the pig has established its acceptability as a model for the study of the burn problems (Evans et al., 1955; Archanbeau et al., 1966; Bustad, 1966; Bustad and McClellan, 1966; McClellan, 1968; Wachtel et al., 1977). Although specific morphological and histochemical differences exist (Montagna and Yun, 1964), comparisons are certainly applicable for the skin, which in pig and man is characterized by a sparse hair coat, a thick epidermis with a well-differentiated low limit, a dermis with a distinct papillary body, a high elastic tissue content (Berkley, 1954; Montagna and Yun, 1964; Archanbeau et al., 1966; Marcarion and Calhoun, 1966) and similarities in vascularization (Forbes, 1969). The findings on the epidermis have been confirmed ultrastructurally (Karasek and Oehlert, 1968a, b). Moreover, the kinetics of epidermal proliferation are comparable in porcine and human epidermis, being about 30 days for porcine epidermis while in the human epidermis it is 26–27 days (Weaver and Stoll, 1969). The enzyme pattern of pigskin is similar to man, particularly for the epidermis, and probably for the accessories of the skin (Mayer and Neurand, 1976).

Moritz and Henriques (1947) have described

porcine skin before and after thermal exposures and compared it to human burns showing the relative vulnerability of porcine and human skin to thermal injury. They were able to show little or no quantitative difference in the susceptibility of human and porcine epidermis to thermal injury at similar surface temperatures. Moritz (1947) delineated the pathogenesis and pathological characteristics of cutaneous burns in relation to the duration and intensity of thermal exposure and to their susceptibility for organization, repair and healing.

Perkins, Pearse and Kingsley (1952) demonstrated comparable surface appearance for similar threshold values (cal/cm^2) for human and porcine skin subjected to radiant energy, in epidermal and intradermal (and perhaps subdermal) burn lesions. Their data were comparable to the values of 2 cal/cm^2 for epidermal burns and 3·5 cal/cm^2 for deep intradermal burns in humans reported by Butterfield and Dixey (1951) and correlated well with the 3·9 cal cm^{-2} s^{-1} (0·54-s exposure) value for subdermal human burns reported by Moncrief (1969).

The heat capacities and thermal conductivities of cutaneous and subcutaneous tissues of the pig, *in vivo* observations of caloric uptake of pig skin and the resulting rise in temperature at the dermis–fat interface as a function of both time and skin surface temperature and an estimation of the temperature changes at the epidermal–dermal interface during the exposure of the skin surface to heat have been reported (Henriques and Moritz, 1947). Moritz et al. (1947) have investigated the mechanisms by which thermal exposures, in which heat is transferred to the body through an envelope of air, cause disability and death.

Pigskin has served as an *in vivo* system for the evaluation and comparison of the effects of different ionizing radiations and the extrapolation of these results to man. The response patterns to irradiations observed in the domestic pigskin are similar to those described for man (Archanbeau et al., 1966).

Furthermore, wound healing in pigs develops essentially as described in man (Gillman and Ordman, 1966). However, extrapolating interpretations from dermatological experiments with animals may only be done with the greatest caution. The pig may react to skin damage more sensitively than man (Meyer and Neurand, 1976). As a result, the skin of the pig and the animal itself is being used increasingly for investigating burn problems.

The previous work by Moritz et al. (Moritz, 1947; Moritz and Henriques, 1947; Moritz et al., 1947), Perkins et al. (1952), Berkley (1954), Lyon et al. (1955), Stoll and Green (1959) and Weaver and Stoll (1969) addressed the understanding of the development of threshold blisters. More recently Takata (1974) using our data (uncorrected for tissue shrinkage) proposed a model for dermal burns. This model, for the first time, addressed tissue water boiling as an important factor in retarding the flow of heat to deeper skin structures. Knox, Wachtel and Knapp (1978b) have presented a slightly different model and point out the need to include both water boiling and corrections to depth measurements to take into account skin shrinkage due to water loss and protein denaturation.

In this paper we have attempted to carry the process of predicting burn damage one step further by using heat flux measured after it passed through a fabric as the input to a model. The results are compared with actual burns produced in pigs by subjecting them to the same thermal source for the same duration. The results (*Table IV–VI*) indicate that while it is possible to obtain some predictions which are well within one standard deviation of observed results, in other cases the observed and predicted results are not close or even in the proper direction.

There appear to be three sources of error in this process which will require further work to understand in detail. First, the process of calculating a time–flux profile is a very unstable process and prone to error. Increased care must be taken to stabilize this process. Secondly, the exposure of the sensors and the pigs was a sequential process and not a parallel process so that slight differences in the thermal source or even regional differences in initial skin temperature could account for much of the variance as could the variability of the fabrics. Even without the model or sensors intervening in the process there is a lot of variance in the bioassay data, as summarized in *Table V*. High variance was also characteristic of the University of Rochester studies in which the heat source was a well-controlled carbon arch lamp (Perkins et al., 1952; Berkley, 1954; Lyon et al., 1955).

Finally, the model itself is still not optimal, in that it over-predicts epidermal burns and under-predicts mid- to deep dermal burns. It would appear that the rate constant and energy of activation, P and ΔE, in the Arrhenius relationship used to calculate the damage as a function of temperature may have to be changed as a function of both temperature (as they are now) and depth.

$$\text{damage rate } d\Omega/dt = Pe^{-\frac{\Delta E}{RT}}$$

In addition, the total calculated damage as a function of depth is very steep at the skin surface, so that smaller depth increments (now 222 μm) may be needed to resolve burn depths in the first 200 μm. Likewise, a better interpolation scheme is necessary to find the threshold depth, which is defined as that depth where $\Omega = 1$.

There is good reason to persue the development of this model to predict burn depth. To evaluate just four fabrics using the bioassay method requires 20 pigs and the services of 8–10 people for approximately 3 months. By contrast, a method using sensors and an optimal model will accomplish the same task with 1–2 people in 3–5 days. So there is a very great economic incentive to move from the bioassay method to the use of sensors and a good model.

As can be seen by the present models' performance (*Table VI*) the use of a sensor and a model is feasible but will require further work before the accuracy of this process is entirely satisfactory.

The prospect of having a model which accurately predicts burn depths over the full thickness of the skin raises the question of being able to predict survival. The survival of a burned patient is influenced by the size and depth of the burn, the age and sex of the patients, topical agents used on the wound and the institution providing treatment (Feller et al., 1976). Each criterion must be considered separately as well as collectively (e.g. there is increased survival of males compared to females and the topical agent did not appear to be significant), and survival curves estimated by probit analysis are available (Feller et al., 1976). However, we know of no good source relating accurate depth measurements with survival. Additional criteria may be useful for characterizing the burned population (Fisher et al., 1977) and necessary for careful classification and analysis of morbidity and mortality data. Survival probability, expected morbidity, length and cost of hospitalization, frequency of long term disability and other measureable treatment goals are the markers by which prevention and determination of the burn injury must be judged. Only then will one be able to balance the feasibility of improving a fire-retardant fabric against the cost of the new technology for developing better thermally protective fabrics and its direct line cost.

Patients in whom burns were associated with clothing ignition had a fourfold increase in mortality (24 *v.* 6 per cent) and a prolonged hospital stay (21 days longer) compared to those patients whose clothing was not burned. Moreover, the body surface area involved for the clothing-related injuries was two times greater than that for non-clothing-related burns, and the area of full-thickness injury was six times greater than that associated with non-clothing-related burns (Feller et al., 1972).

Critical temperatures detrimental to living cells persist for a considerable length of time (Moserova et al., 1975). If mathematical models can be used with physical sensors to test thermally protective fabrics with accuracy and predictability, then many fabrics can be compared at relatively low cost and in replications sufficient to give clinically acceptable and meaningful data. Prevention then becomes a realistic goal backed by criteria that will allow the designer and user to weigh the thermal protective capability against appearance, comfort, durability, colour fastness, launderability and cost.

BIBLIOGRAPHY

Aerotherm Corporation (1970) Users Manual, Aerotherm Charring Material Thermal Response and Ablation Program, version 3. AFRPL-TR-70-92.

Archanbeau J. O., Fairchild R. G. and Commerford S. L. (1966) Response of the skin of swine to increasing exposure of 250-KVP X-ray. In: Bustad L. K. and McClellan R. O. (ed.) *Swine in Biomedical Research*. Seattle, Frayn, p. 463.

Berkley K. M. (1954) Evaluation of Surface Appearance of Burns by Depth of Damage. University of Rochester Atomic Energy Report. UR-337.

Bustad L. K. (1966) Pigs in the laboratory. *Sci. Am.* **214,** 94.

Bustad L. K. and McClellan R. O. (ed.) (1966) *Swine in Biomedical Research*. Seattle, Frayn.

Butterfield W. S. H. and Dixey J. R. B. (1951) Burns from atomic bombs. *J. R. Nav. Med. Sci.* **37,** 9.

Evans E. I., Brooks J. W., Schmidt F. H. et al. (1955) Flash burn studies on human volunteers. *Surgery* **37,** 280.

Feller I., Flora J. D. and Bawol R. (1976) Baseline results of therapy for burned patients. *JAMA* **236,** 1943.

Feller I., Richards K. and Crane K. (1972) The role of flammable fabrics in severe burn injuries. In: *Proceedings of the Sixth Annual Meeting of the Information Council on Fabric Flammability.*

Fisher J. C., Wells J. A., Fulwider B. T. et al. (1977) Do we need a burn severity grading system? *J. Trauma* **17,** 252.

Forbes P. D. (1969) Vascular supply of the skin and hair in swine. In: Montag W. and Dobson R. L. (ed.) *Hair Growth, Advances in Biology of Skin.* Oxford, Pergamon, pp. 9, 479.

Gillman T. and Ordman L. (1956) Histogenesis of healing incised and excised wounds in young pigs. In: Bustad L. K. and McClellan R. O. (ed.) *Swine in Biomedical Research*. Seattle, Frayn, p. 299.

Henriques F. C. and Moritz A. R. (1947) Studies of thermal injury. I. The conduction of heat to and through skin and the temperatures attained therein, a theoretical and an experimental investigation. *Am. J. Pathol.* **23,** 531.

Karasek J. and Oehlert W. (1968a) Die Ultrastructure der Epidermis des Schweines. I. Stratun Basale und Stratum Spinosum. *Z. Mikrosk. Anat. Forsch.* **78,** 133.

Karasek J. and Oehlert W. (1968b). Die Ultrastruktur der Epidermis des Schweines. II. Stratum Granulosum und Corneum. *Z. Mikrosk. Anat. Forsch.* **79,** 157.

Knox F. S., Knapp S. C., Wachtel T. L. et al. (1979) Bioassay of thermal protection afforded by candidate flight suit fabrics. *Aviat. Space Environ. Med.* (In the press).

Knox F. S., McCahan G. R. and Wachtel T. L. (1974) Use of the pig as a bioassay substrate for evaluation of thermal protective clothing and physical sensor calibration. *Aerospace Med.* **45,** 933.

Knox F. S., Wachtel T. L. and Knapp S. C. (1978a) Biomedical constraints on thermal protective flight clothing design: a bio-engineering analysis. In: *Proceedings of North Atlantic Treaty Organization Advisory Group for Aerospace Research and Development: Operational Helicopter Aviation Medicine, Fort Rucker, Alabama.* (In the press.)

Knox F. S., Wachtel T. L. and Knapp S. C. (1978b) Mathematical models for skin burns induced by simulated post-crash fires as aids in thermal protective clothing design and selection. In: *Proceedings of the Army Scientific Conference, West Point, New York.* (In the press.)

Knox F. S., Wachtel T. L., Trevethan W. P. et al. (1978c) A porcine bioassay method for analysis of thermally protective fabrics: IA histopathological and burn depth grading system. Fort Rucker, Alabama, US Army Aeromedical Research Laboratory, USAARL Report No. 78.

Lyon J. L., Davis T. P. and Pearse H. E. (1955) Studies of flash burns: the relation of thermal energy applied and exposure time to burn severity. University of Rochester, Atomic Energy Report UR-394.

McClellan P. O. (1968) Application of swine in biomedical research. *Lab. Anim. Care* **18,** 120.

McCoy J. A., Micks D. W. and Lynch J. B. (1968) Discriminant function probability model for predicting survival in burned patients. *JAMA* **203,** 644.

Marcarian H. Q. and Calhoun M. L. (1966) Microscopic anatomy of the integument of adult swine. *Am. J. Vet. Res.* **27,** 765.

Meyer W. and Neurand K. (1976) The distribution of enzymes in the skin of the domestic pig. *Lab. Anim.* **10,** 237.

Moncrief J. A. (1969) Burns. In: Schwartz S. I. (ed.) *Principles of Surgery*. New York, McGraw Hill, p. 205.

Montagna M. and Yun J. S. (1964) Skin of the domestic pig. *J. Invest. Dermatol.* **43,** 11.

Moritz A. R. (1947) Studies of thermal injury. III. The pathology and pathogenesis of cutaneous burns: an experimental study. *Am. J. Pathol.* **23,** 915.

Moritz A. R. and Henriques F. C. (1947) Studies of thermal injury. II. The relative importance of time and surface temperature in the causation of cutaneous burns. *Am. J. Pathol.* **23,** 695.

Moritz A. R., Henriques F. R., Dutra F. R. et al. (1947) Studies on thermal injury. IV. An exploration of the casualty producing attributes of conflagration. *Arch. Pathol.* **43,** 466.

Morton J. H., Kingsley H. D. and Pearse H. E. (1952) Studies on flash burns: threshold burns. *Surg. Gynecol. Obstet.* **94,** 317.

Moserova J., Behounkova E. and Prouza Z. (1975) Subcutaneous temperature measurements in a thermal injury. *Burns* **1,** 267.

Perkins J. B., Pearse H. E. and Kingsley H. D. (1952) Studies on flash burns: the relation of the time and intensity of applied thermal energy to the severity of burns. University of Rochester, Atomic Energy Report, UR-217.

Stoll A. and Greene L. C. (1959) Relationship between pain and tissue damage due to thermal radiation. *J. Appl. Physiol.* **14,** 373.

Takata A. (1974) Development of criterion for skin burns. *Aerospace Med.* **45,** 634.

Wachtel T. L., Knox F. S. and McCahan G. R. (1978) A porcine bioassay method for analysis of thermally protective fabrics. I. A clinical grading system. Fort Rucker, Alabama, US Army Aeromedical Research Laboratory, USAARL Report No. 78.

Wachtel T. L., McCahan G. R. and Knox F. S. (1977) Methods of preparing porcine skin for bioassay of thermal injury. *Milit. Med.* **141,** 536.

Wachtel T. L., McCahan G. R. and Monafo W. W. (1977) Fluid resuscitation in a porcine burn shock model. *J. Surg. Res.* **23,** 405.

Weaver J. A. and Stoll A. M. (1969) Mathematical model of skin exposed to thermal radiation. *Aerospace Med.* **40,** 24.

Weinstein G. D. (1966) Comparison of turnover time of kerakinous protein fractions in swine and human epidermis. In: Bustad L. K. and McClellan R. O. (ed.) *Swine in Biomedical Research*, Seattle, Frayn, p. 287.